Deep Dive on Current and Future Flash Technology

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Agenda

1. NAND Fundamentals and Trends
2. SSD Endurance
3. Emerging NAND Technologies

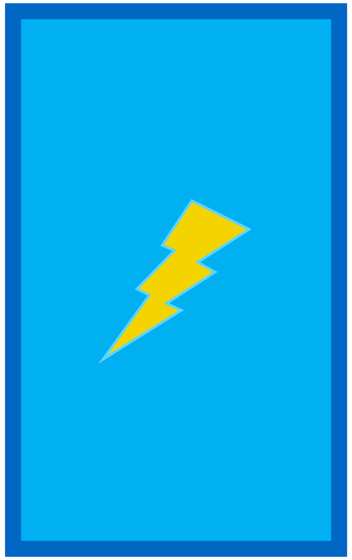
Fundamentals of Solid State

- SSDs are closer to memory than hard drives in terms of performance and endurance.
  - Much higher performance than HDD
  - Metrics for endurance are very different, new terms apply
- Solid-state technology is changing at a much faster rate than HDD
  - New capacities yearly, following the changes in wafer density
  - Multiple new technologies in development across NAND and storage-class memory
- Key takeaways from this session:
  - Understand the terms which define the performance and reliability of SSDs
  - Understand the standard endurance metrics which can be used to compare SSDs across vendors
  - Know how this applies to your deployment

NAND Fundamentals and Trends

NAND Types and the Shift to 3D NAND

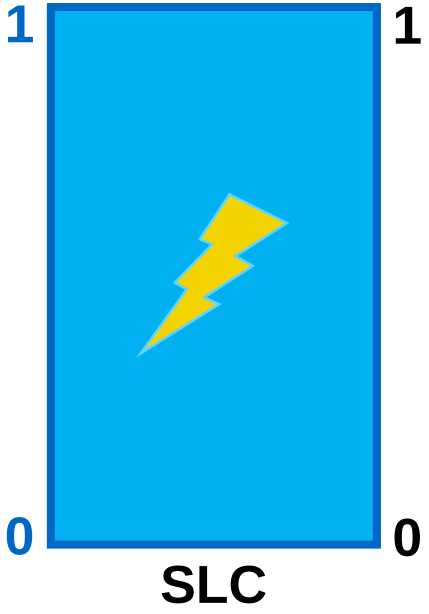
Basics of a NAND Cell



- A NAND cell is:
  - A container which stores a charge (electrons)
  - Surrounded by a permeable barrier to hold the charge
- A charge is stored in the cell
  - A charge is applied to insert electrons into the cell
  - The voltage amount determines the cell value
- NAND is non-volatile memory
  - Data is maintained across power cycles
  - The barrier requires power to release its charge

Evolution of NAND Density

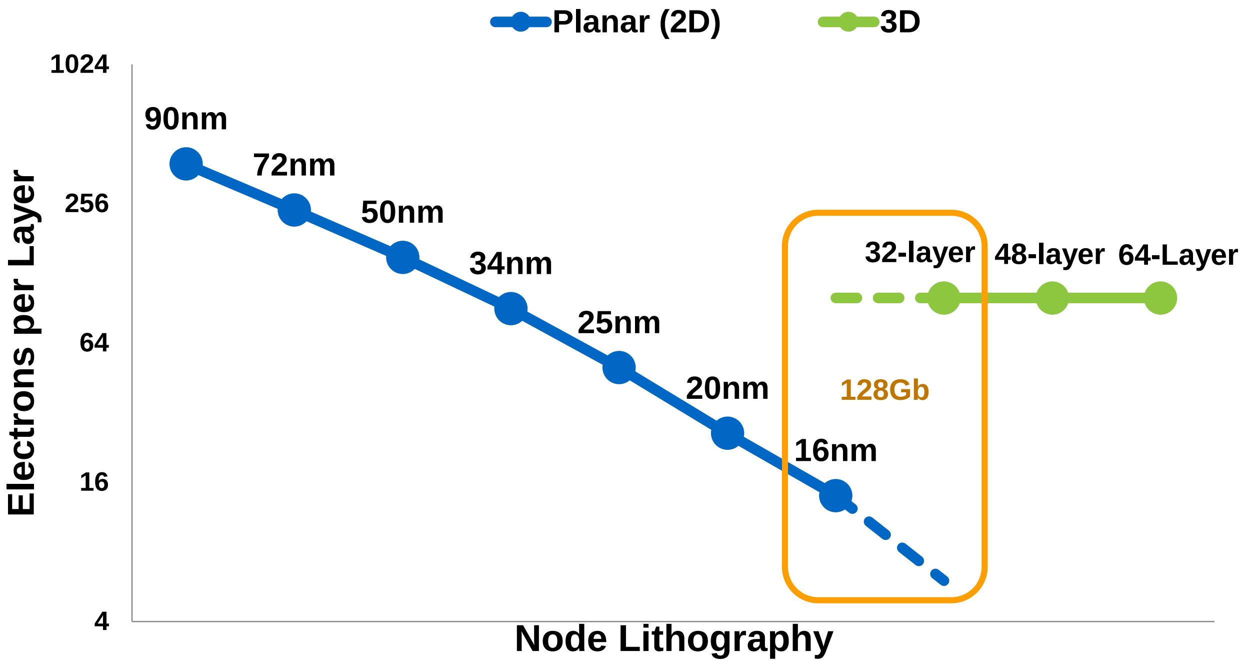
Increasing Densities of NAND Cells



Shift from Planar (2D) to 3D NAND

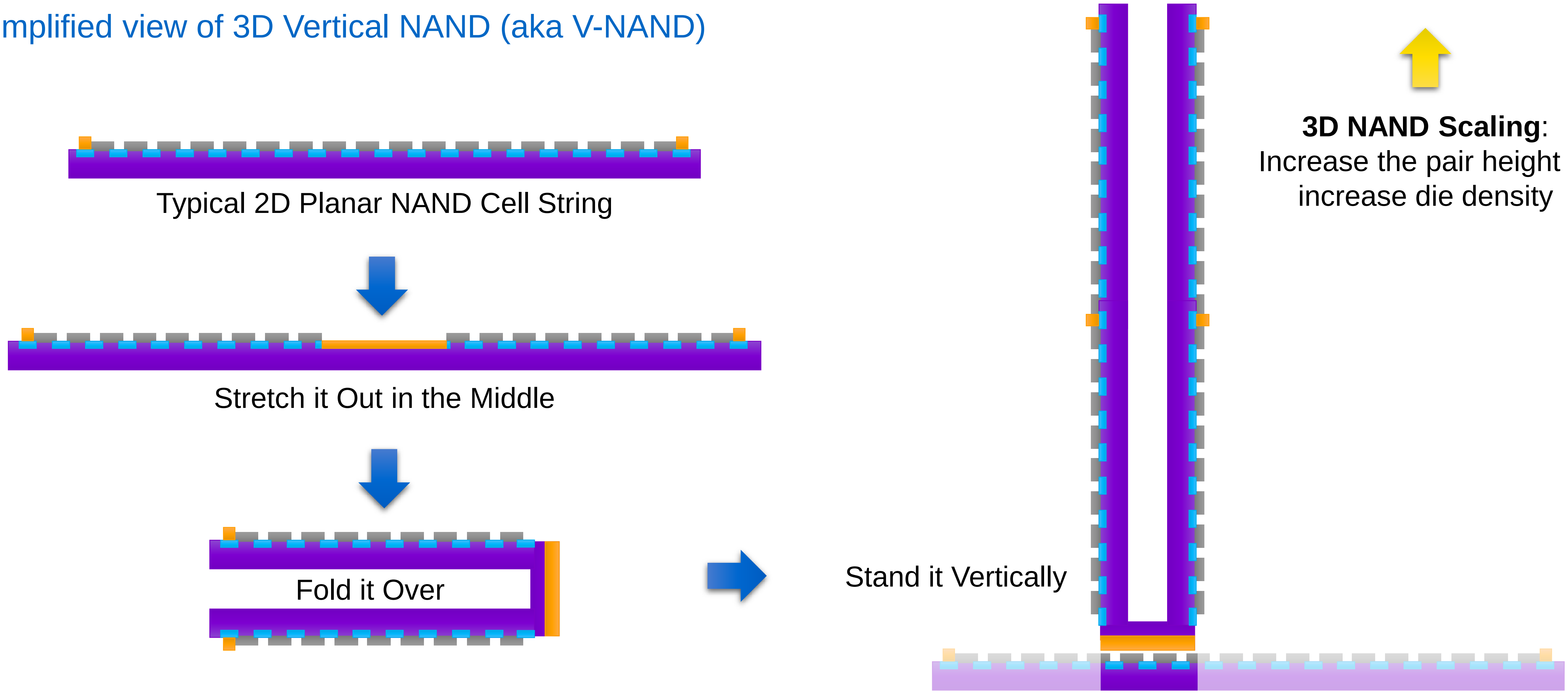
Scalability with reliability

- Shrinking planar cell holds less charge
  - Fewer electrons to distinguish between “0” and “1”
  - Small loss / gain of electrons can cause a bit flip
  - Fewer program / erase (P/E) cycles supported
- 3D NAND uses larger cells
  - More differentiation between bit states
  - Less interference between cells
  - Improved P/E support over planar NAND
- Increased scalability with 3D NAND
  - Planar NAND density is limited to 128Gb / die
  - 3D NAND density starts at 128Gb / die



Getting from Planar NAND to 3D NAND

Simplified view of 3D Vertical NAND (aka V-NAND)



Typical 2D Planar NAND Cell String

Stretch it Out in the Middle

Fold it Over

Stand it Vertically

3D NAND Scaling: Increase the pair height to increase die density

3D NAND uses less wafer area than 2D for the same bit density

Key Benefits of 3D NAND

- Endurance
  - Larger cell geometry provides more differentiation between bit states for MLC / TLC
  - Program / erase (P/E) cycle improved over planar NAND (and will continue thru ~2020)
- Density
  - Larger die sizes, along with bigger pages and blocks increases, overall density
  - Adding layers increases scalability while maintaining reliability
  - Smaller capacities become a challenge as layers increase
    - Planar NAND (15 / 16nm) will remain for several years to meet smaller scalability needs
- Power
  - New cell barrier technology (charge trap versus floating gate) reduces power consumption for program/erase
- Performance
  - Much better write performance over planar NAND
  - Read access times generally comparable to planar NAND

NAND Outlook

Near-term view of NAND Transitions

- NAND volume is currently shifting from planar 2D NAND to 3D NAND
  - Foundries are shifting volume production to new 3D NAND through 2017
  - Current 2D-node lithography (16-15nm) will remain for a few more years, primarily for smaller capacities
- All major NAND foundries have announced 3D-NAND SSDs
  - Samsung continues to lead production shipments of 3D NAND
  - Remaining foundries are transitioning to 3D NAND through 2016 / 2017
- Density
  - 128Gb/die will be highest planar 2D die density
  - 3D NAND has transitioned to 256Gb/die, with projections of 1Tb/die in future generations
  - QLC (MLC 4-bit) on the planning horizon, although remains several years away for production
- NAND remains least expensive ($/GB) non-volatile memory for the foreseeable future

SSD Endurance

Fundamentals of Solid-State Reliability

SSD Endurance Metrics

Measuring the reliability of an SSD

NAND Type != Endurance

- NAND is evolving quickly – NAND type (SLC, MLC, TLC) is not an indicator of endurance
  - The transition to 3D NAND changes the landscape for how endurance is measured
  - NAND type becomes a measure of scalability and cost efficiency

Old View

Type	Endurance
SLC	Best
eMLC	Better
cMLC	Good

New View – Coming Soon

SSD Endurance Factors

Knowing which SSD to choose

- Many factors affect SSD endurance ratings: “Your mileage may vary...”

Warranty

P/E Cycle Rating

Workload

Over-Provisioning %

SSD Capacity

Write Amplification

Voltage

Total Bytes Written

Data Retention at End of Life

Choosing the Right SSD

Matching endurance to workload

How Do I Know What To Choose?

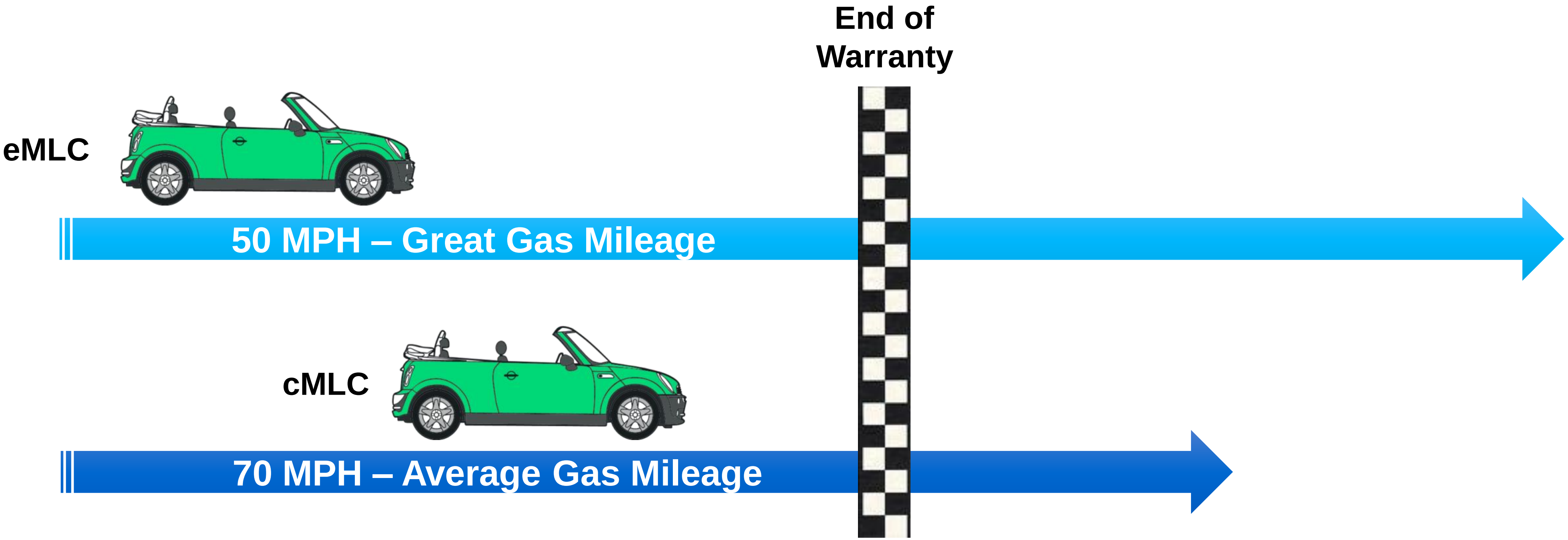
NetApp® Engineering does this work for you.

- Reliable performance and endurance for the full warranty period of the flash system
  - Tested across a variety of workloads and use cases
  - Extended warranty available, no caveats on usage
- Each flash system has unique requirements – SSDs are tailored to match
  - Validated against actual performance history (from AutoSupport)
  - Ensures all workloads are supported regardless of use case (Flash Pool™, hybrid, All Flash FAS, EF-Series, SolidFire®, etc)

SSD Endurance Fundamentals

- Program / Erase (P/E) cycles
  - SSDs have a finite lifetime, dictated by the number of write operations (P/E cycles) NAND cells can endure
  - Once the P/E cycles have been exceeded, the SSD cells are subject to wear-out
    - The permeable barrier around the cell begins to break down, allowing electrons to “leak” out
    - Bit errors occur when the charge can no longer be reliably determined, even with ECC (error-correcting code)
- A note on voltage
  - Using higher voltages to program NAND cells improves I/O performance, but accelerates wear-out
  - By writing to the flash more gently, the technology can be made to last considerably longer
  - This is the primary difference between eMLC and cMLC
    - eMLC = 20,000 to 30,000 P/E cycles, but slower programming speeds
    - cMLC = 3,000 to 10,000 P/E cycles

An Example of Endurance



End of Warranty

eMLC

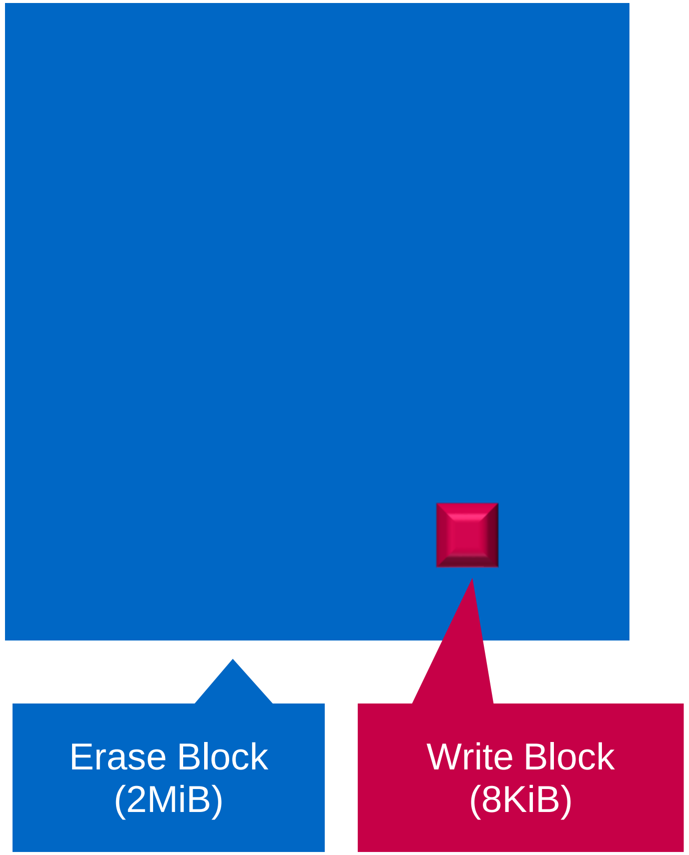
50 MPH – Great Gas Mileage

cMLC

70 MPH – Average Gas Mileage

Write Amplification

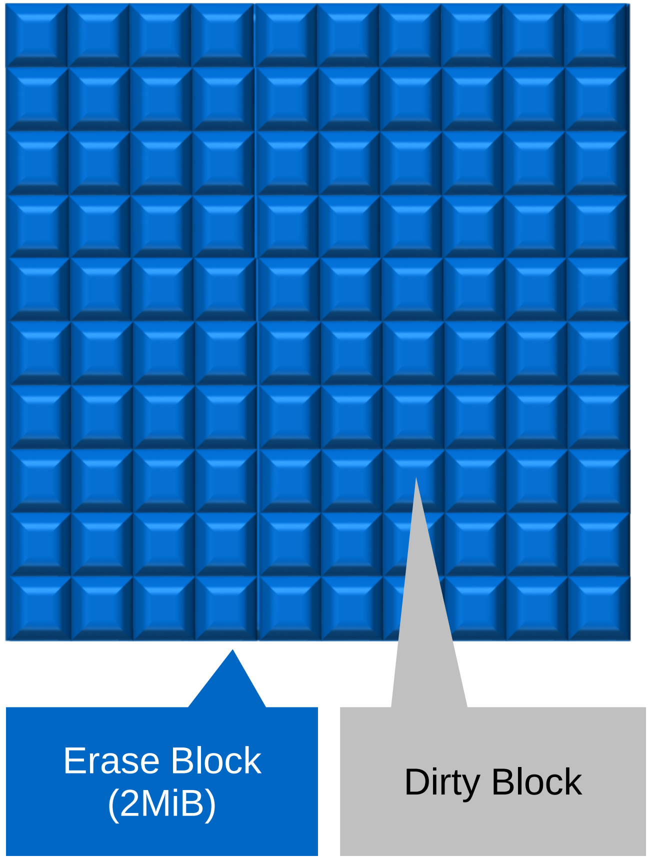
Unique characteristic of SSDs



- NAND flash must be erased before rewrite
  - Erase block is much larger than write block
  - Re-writing a block forces a rewrite of full erase unit
- Write amplification is
  - An aggregate measure of program / erase cycles
  - Caused by rewrite activity to a used block
- Write amplification example using fixed mapping
  - 4KiB block = 2MiB / 4KiB 512x WA
  - 32KiB block = 2MiB / 32KiB 64x WA

Reducing Write Amplification

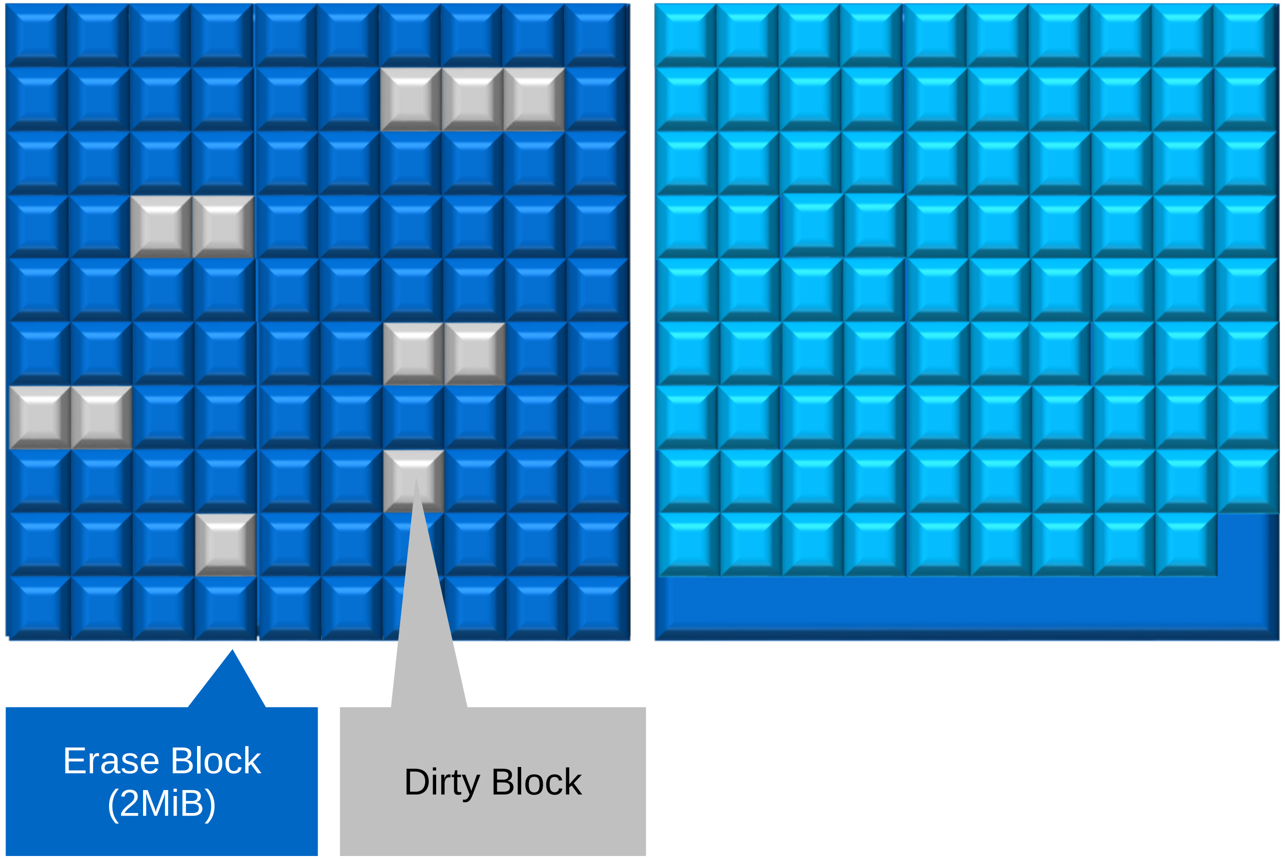
SSD Flash Translation Layer



- The Flash Translation Layer (FTL)
  - Abstraction layer between host address and on-disk data location
  - FTL can move on-disk data location as needed
- The FTL logs overwrite as they occur
  - New data is written to a new location
  - “Dirty” (not current) data is marked for deletion
  - Erased blocks are logged as dirty blocks as well
- Write amplification is reduced by deferring P/E cycle
  - Over time, block fragmentation occurs
  - Dirty blocks accumulate and need cleanup

Garbage Collection

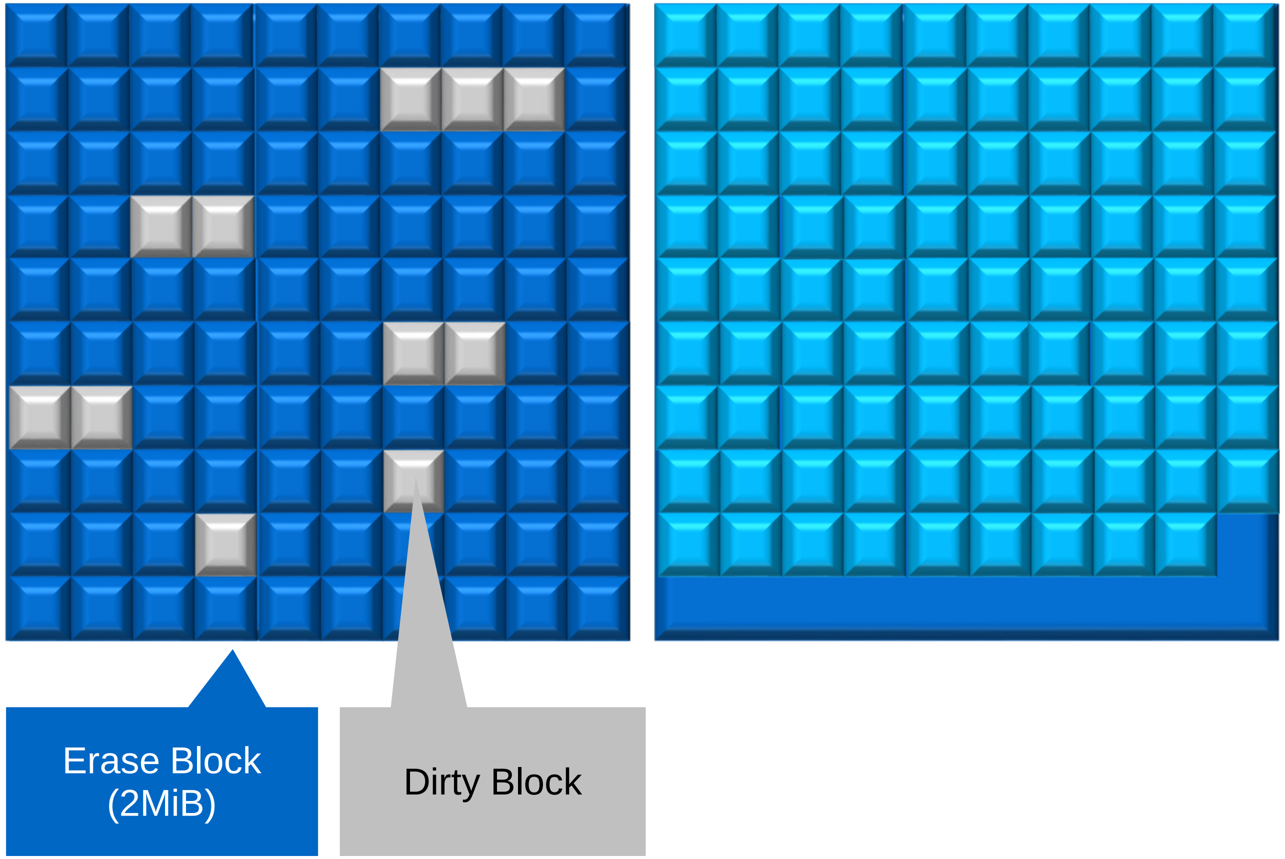
Reclaiming space



- The FTL can reclaim fragmented space
- To do that it must “garbage collect”
  - First read data blocks to be retained
  - Then write those blocks into an available erase block (free space on media)

Garbage Collection

Reclaiming space

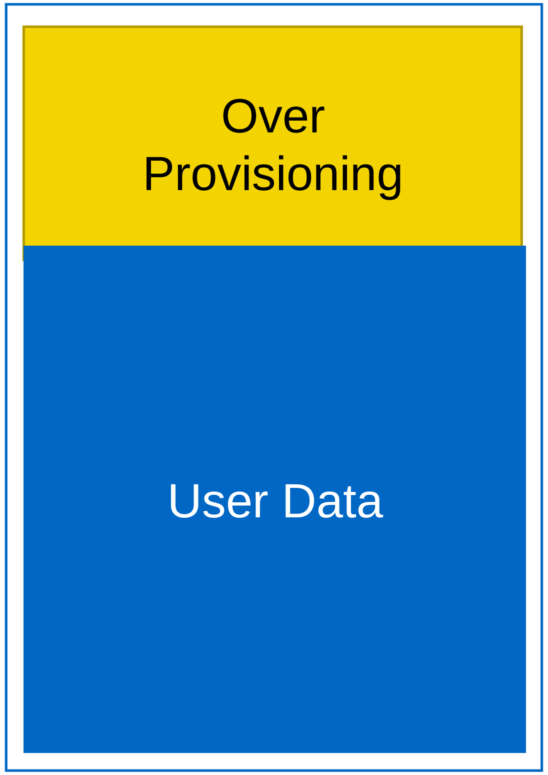


- The FTL can reclaim fragmented space
- To do that it must “garbage collect”
  - First read data blocks to be retained
  - Then write those blocks into an available erase block (free space on media)
  - Finally erase and prepare the erase block for new writes
- Garbage collection increases free space

Over Provisioning and Wear Leveling

Ensuring SSD performance and endurance

- Garbage collection needs “swap” space to operate efficiently
  - Over-provisioning (OP) guarantees that swap space is available
  - Reserved capacity on the SSD that can not be accessed by the user
  - Higher workloads need more OP space, read-intensive workloads need less
- The FTL will attempt to use all NAND erase blocks equally
  - Wear-leveling across all blocks to reduce the wear on individual cells
  - The OP area isn’t a fixed on-disk location, only a fixed capacity



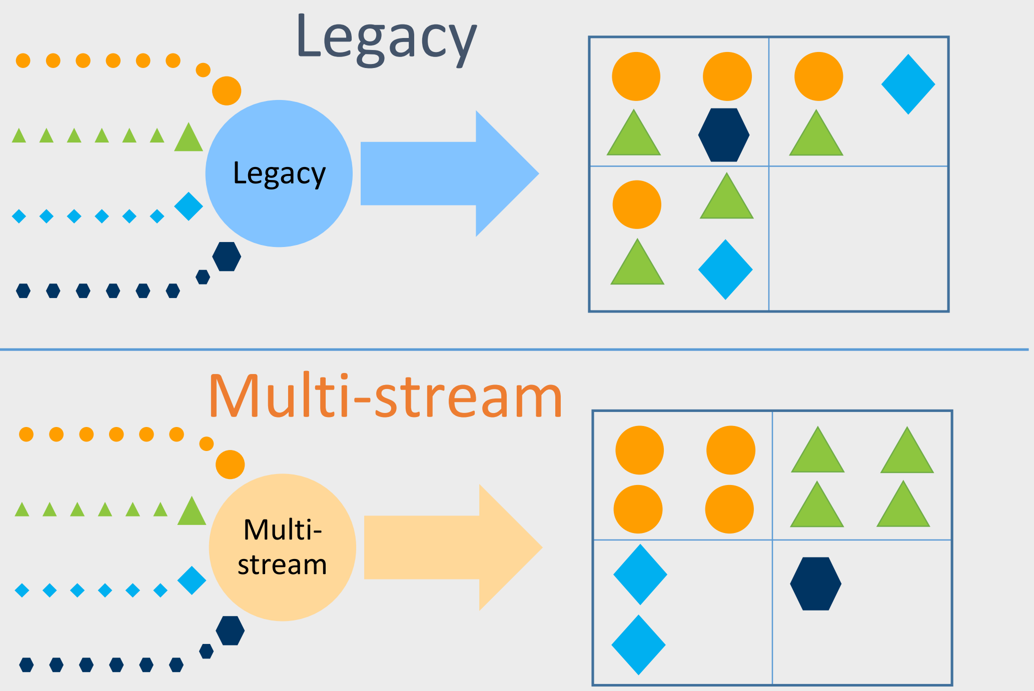
Multi-Stream Write

Reducing write amplification for SSDs

- Enables greater control and efficiency for data placement
  - Reduces the over-provisioning requirements by up to 20%
  - Enables more efficient data placement on the SSD by the operating system
  - Allows writes to be tagged, enabling the FTL to make better decisions over data placement
- T10 standard endorsed by all major SSD vendors
  - First vendor shipments begin in 2016
  - Full support by 2017

Data Placement Control

Highly efficient data placement inside SSD according to data characteristics (for example, controller, aggregate and other)

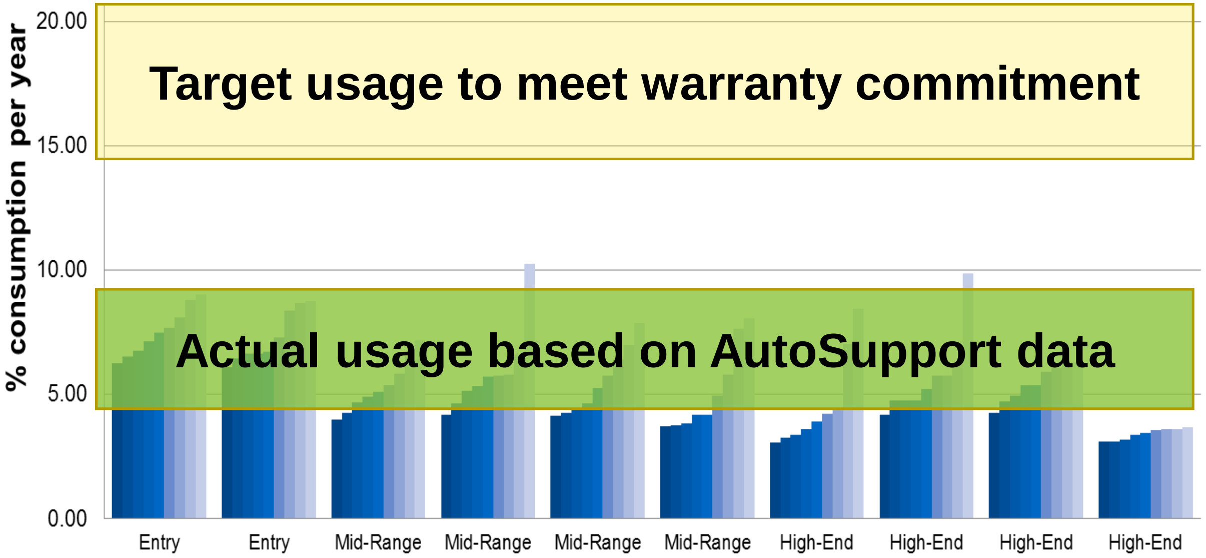


Total Bytes Written

NetApp AutoSupport (ASUP) Analysis

- Total bytes written (TBW)
  - Defines how much total data can be written to the SSD over the life of the drive
  - Based on
    - P/E cycle rating
    - Raw capacity
    - Expected write amplification

- NetApp® has a rich resource in ASUP for reporting real world SSD usage
  - SSDs report actual usage of "rated life used" across our installed base of SSD media
  - Reported as a % of TBW rating for the drive



SSD Endurance Metrics

Measuring the reliability of an SSD

- Drive writes per day (DWPD) is the primary metric for SSD endurance
  - How many times can the full SSD be written per day, for the full warranty period?
  - Used alongside of total bytes written to evaluate SSD endurance over the life of the device
  - A calculation based on
    - P/E cycle rating
    - Expected lifetime of the drive (aka warranty period)
    - Average write amplification (assuming a mixed read/write workload similar to SPC1)
    - Percentage of overprovisioned capacity

Old View

Type	Endurance
SLC	Best
eMLC	Better
cMLC	Good

New View

DWPD	Endurance Descriptions	
25	High Endurance	High End
10	Mainstream	High End
3	Value Endurance	Mid-Range
1	Read Intensive	
.5	Very Read Intensive	

MLC

TLC

DWPD — What Does It Really Mean?

Extreme use case example

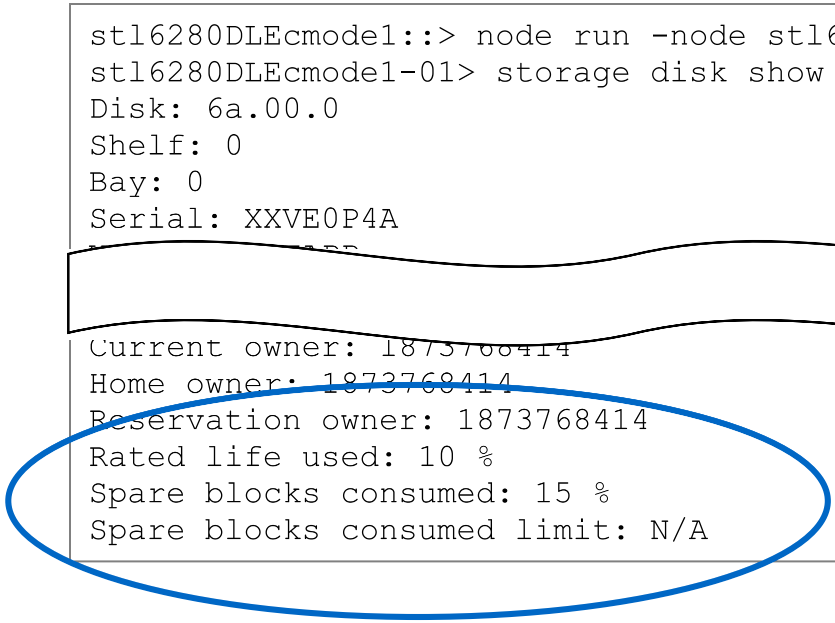
- All Flash FAS (AFF) A700 performance for 100% large, sequential writes is ~ 6500 MB/s
  - 100% writes every minute, all day would ingest 535 TB / day
  - Overwrite the same drives at max performance every day for 5 years
- How to handle this workload?

	960GB	**3.8T**	**15.3T**
# Drives	96	96	48
Raw Capacity	92.2TB	368.7TB	737.3TB
DWPD	3	1	1
% OP	7%	7%	7%
Throughput (TB / day)	**276.4**	**368.7**	**737.3**

Real-World SSD Usage

End-user reporting via ASUP

- AutoSupport field data reports key SSD usage metrics via <storage disk show> command
  - Rated life used – estimate based on
  - Spare blocks consumed - % of OP that has been consumed
  - Spare blocks consumed limit – threshold for trigger an ASUP event (in reality set at 90%)



```
stl6280DLEcmode1::> node run -node stl6280DLEcmode1-01
stl6280DLEcmode1-01> storage disk show -a 6a.00.0
Disk: 6a.00.0
Shelf: 0
Bay: 0
Serial: XXVE0P4A

Current owner: 1873768414
Home owner: 1873768414
Reservation owner: 1873768414
Rated life used: 10 %
Spare blocks consumed: 15 %
Spare blocks consumed limit: N/A
```

Emerging NAND Technologies

Changing landscape of Solid State

NVM Express (NMVe) Overview

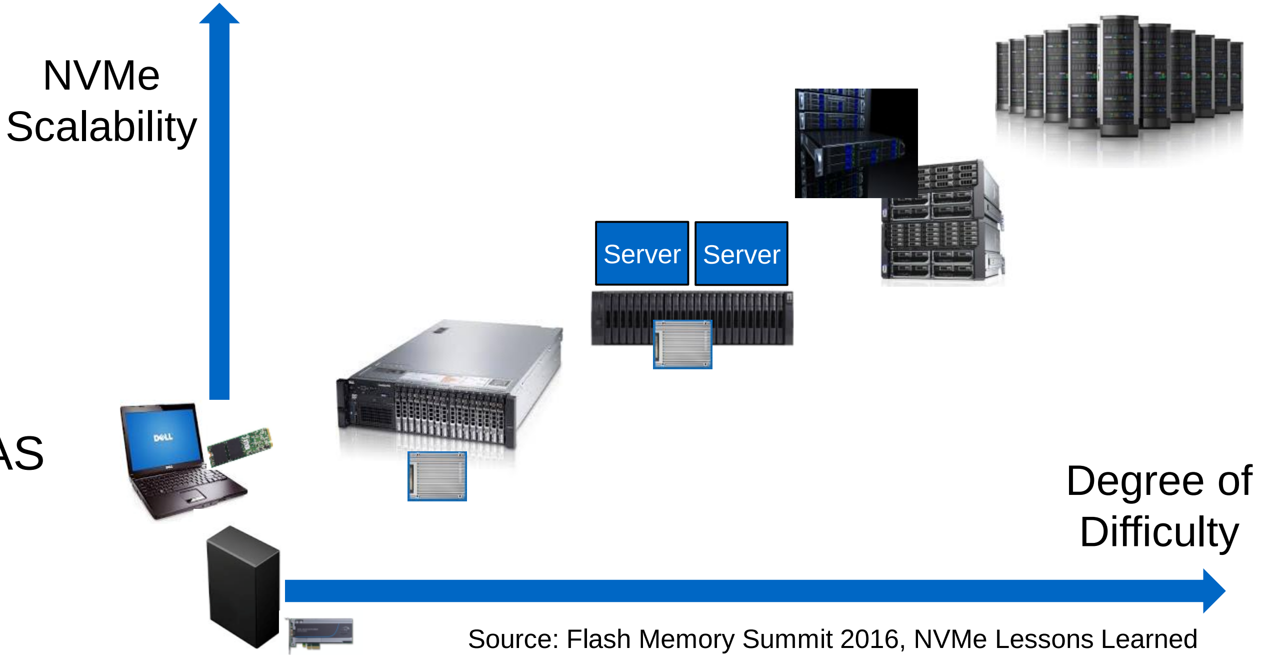
Next-Generation SSD Interface

- NVMe is a communication protocol developed specifically for SSDs
  - Utilizes high performance PCIe for connectivity to compute resources
  - Options for 2.5” SFF or M.2 (internal memory stick) form factors
- Benefits:
  - Efficiency = performance: low CPU utilization, low latency (streamlined interface)
  - Parallelism = performance; multiple cores, OS parallelism, I/O (64K queues, 64K queue depth)
- Challenges
  - PCIe does not natively hot-plug
    - Server / storage vendors have implemented solutions for “planned hot-plug”
    - “Surprise hot-plug” solutions are still under investigation
  - Lacks expansion capability outside the controller chassis
    - NVMe over fabric solutions underway to enable rack scale solutions

NVMe Adoption in the Industry

Server and storage adoption trends

- NVMe is overtaking SATA for internal SSD use
  - Internal cache
  - Data storage
  - NVMe $/GB will soon surpass SATA $/GB
- Server adoption underway
  - Single ported NVMe ideal for DAS
  - Strong performance for server uses
- Storage adoption on the horizon
  - Dual-ported NVMe needed to support HA pairs
  - Cost of dual-port NVMe not competitive with SAS

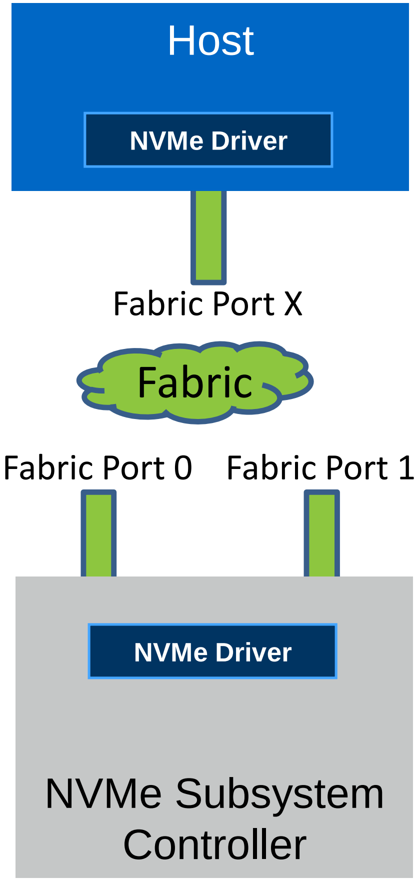


Source: Flash Memory Summit 2016, NVMe Lessons Learned

NVMe Over Fabrics

Expanding the NVMe Protocol beyond the chassis

- Extending NVMe over different fabric types
  - Maintains the benefits of NVMe across external connections
  - First definition is the RDMA protocol
    - Ethernet (iWARP and ROCE)
    - Infiniband
- Goals
  - Maintain end-to-end NVMe protocol, no translation
  - Equivalent IOPS performance between internal / external NVMe
  - Scalable to 100s of SSDs, well beyond PCIe-based attach



Dynamic SSD Capacity

Extending the usable lifetime of NAND SSDs

- As with HDDs, SSDs have capacity reserved for managing bad blocks within the SSD
  - Bad blocks could occur due to faulty dies, wear-out and more
  - The reserved block of capacity is not available for end use
  - If the number of bad blocks exceeds the reserved capacity, the SSD is failed

Actual NAND	0% OP	7% OP	28% OP
1024GB	1000GB	960GB	800GB
4096GB	4000GB	3840GB	3200GB

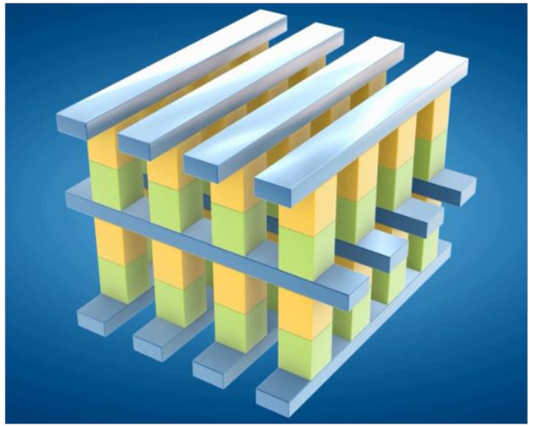
- Dynamic capacity would resize the SSD rather than fail due to excessive errors
  - Example: SSD to continue operations in the event of one or more bad dies on the SSD
  - Bad blocks would be marked and set as unused space by the SSD and the host
  - SSD usable space would be reset: for example, 800GB becomes 700GB

- Proposed standard – jointly developed by NetApp® and SSD vendors

Storage-Class Memories

Long-Term Alternatives to NAND

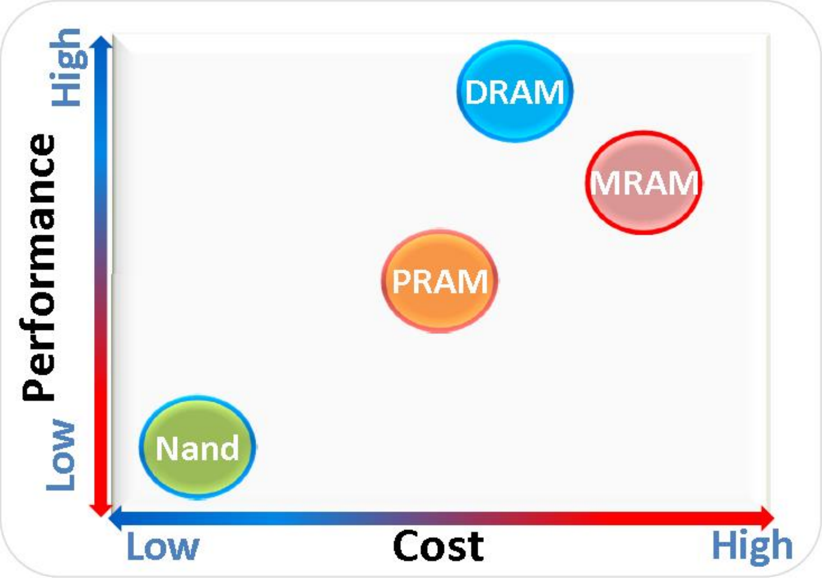
- Storage-class memories are “resistive” devices with long-term scalability
  - DRAM, NAND and HDDs are all electron devices, and ultimately face scaling challenges
- Multiple technologies are in development
  - 3DXpoint = Intel Optane (phase-change memory), can scale to additional layers and multiple bits per cell
  - STT-MRAM = spin-transfer torque magnetic RAM — closest to DRAM in speed and cost
  - ReRAM = Resistive RAM — huge potential in the future, not likely before 2020



Storage-Class Memory Comparison

	DRAM	MRAM	PRAM	NAND
Endurance	>10^{15}	>10^{15} *	~10^{7}	3 x 10^{3}
Operation Type	Byte	Byte	Byte	Page
Write Latency	≤ 15ns	≤ 45ns	~ 2µs *	~1.3ms
Read Latency	≤ 15ns	≤ 45ns	~110 ns *	~60µs
Retention	64ms	10 year *	10 years	10 years

* Target – still in development



Long-Term NAND Outlook

- NAND remains the dominant non-volatile memory technology through 2020
  - Price / performance are better suited for large-scale storage in near term
  - NAND remains the cheapest non-volatile memory ($/GB) for the foreseeable future

- Storage-class memory is an emerging market with high growth potential
  - Near-term replacement for DRAM for data retention and scalability
  - Current cost profile limits deployments to internal memory applications

Key Takeaways

- The transition to 3D NAND introduces new scalability with higher endurance.
- SSD endurance is dependent on many factors, including workload.
- NetApp® selects the right SSD for our system's workload profile.

Related Sessions and Resources

Learn More About this Topic

- 60616-2: Comparing Modern All-Flash Architectures
- 61692-2: All Flash FAS Technical Deep Dive
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